

Planar Diode Multiplier Chains for THz Spectroscopy

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Abstract— Broadband frequency multiplier chains based on planar GaAs Schottky diodes [1], developed for the Herschel Space Observatory (Herschel) [2] and ALMA [3], have been applied to high-resolution laboratory spectroscopy covering most frequencies from 0.2 to 2.5 THz. These chains are driven by commercially available frequency synthesizers and millimeter wave multipliers (6x), which provided a broadband RF source with several mW from 70 to 120 GHz. The millimeter wave signal is amplified with recently developed power amplifiers [4] to more than 100 mW with 15% bandwidth to drive cascaded multipliers [5] - [8]. These multipliers are cascaded with up to 4 successive doublers or triplers with a multiplication factor of 2 to 36. By selecting well-matched multiplication stages, sufficient power over 10% bandwidth is generated.

High-resolution laboratory spectroscopy is utilized as a diagnostic tool to determine noise and harmonic content of balanced [9]-[11] and unbalanced [12]-[14] multiplier designs. Balanced multiplier designs suppress unintended harmonics more than -20dB. Much smaller values were measured on unbalanced multipliers.

Index Terms—high-resolution spectroscopy, THz, cascaded frequency multipliers, planar GaAs Schottky diode, noise level and harmonic content

I. INTRODUCTION

THE development of all-solid-state frequency sources for THIFI (Heterodyne Instrument for the Far-Infrared) and ALMA (Atacama Large Millimeter Array) has provided broadband RF sources without mechanical tuners in the THz regime. Frequency coverage is central in all remote sensing experiments. Historically atmospheric chemistry instruments like MLS [15] have relied on wide band IF mixers to achieve coverage, while astrophysics missions like SOFIA [16] and [17], ALMA [3], and Herschel use both wide band mixers and multiple local oscillator sources. In all cases, precise frequency knowledge and spectral purity must be maintained in order to obtain accurate observations of molecular and atomic transitions. Laboratory high-resolution spectroscopy provides atomic and molecular data that enables interpretation of atmospheric chemistry observations, remote and local

planetary observations, and spectroscopic astrophysical observations.

The challenges in laboratory spectroscopy are similar to the remote sensing one in terms of the need for bandwidth and spectral purity, but there is a difference in that the spectrometer can be re-adjusted by the operator as needed. Unfortunately, such re-adjustment is time-consuming and complicates the collection of comprehensive data. A primary limitation in traditional millimeter and submillimeter spectrometers is the tuning range of the phase lock loop. To avoid this limitation a commercially available frequency synthesizer with a high quality internal lock loop was utilized. If the spectral purity of the synthesizer is sufficient, direct multiplication with planar multipliers and MMIC amplifiers, described herein, allows nearly autonomous operation for rapid collection of data at sub-millimeter wavelengths [18]. As a demonstration, we conducted a series of high-resolution spectra of rotational transitions of isotopomers of H₂O (water), HOCl (hypochlorous acid), and CH₃OH (methanol). The results will be published.

In addition, the spectroscopic techniques provide information on the harmonic content and the noise level of the signal source. In local oscillator applications, it is very important to suppress the harmonics, especially the higher frequency ones which cannot be cut-off by the output waveguide. Balanced multipliers, which can be designed in a symmetric or anti-symmetric configuration, suppress the higher harmonics per design. The symmetry of the diodes arrangement prevents unwanted odd or even harmonics to the order of -20dB to -30dB. It has been observed that the bias conditions strongly impact the generation of harmonics in all tested multipliers. Higher harmonics are spurious signals [20], which can introduce ghost-lines making interpretation of the data more difficult or impossible. This is especially true in unbalanced designs where unwanted harmonics could be higher than the desired ones. The suppression of unwanted harmonics is very important when high spectral purity of the LO [19] is required, as it is the case for laboratory spectroscopy and in heterodyne systems using wideband Hot Electron Bolometers (HEB). Since HEBs are sensitive to amplitude modulation (AM) of incident RF power, AM noise at the modulation frequency impacts the signal to noise ratio. Additionally, in heterodyne systems the system stability is reduced by AM noise because the receiver gain is modulated which prevents efficient integration of the signal. In order to characterize the local oscillators two different spectrometers,

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described in the next sections, were utilized.

II. SPECTROMETER

A. General Description

One of the important components in a spectrometer or a receiver system is a frequency locked source with knowledge of the precise frequency (figure 1).

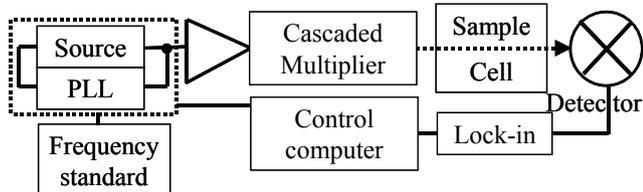


Fig. 1: Block diagram of a spectrometer.

A frequency standard with an accuracy of at least a factor 10x higher than the targeted resolution of the spectrometer is required. In the laboratory this translates to at least a part in 10^9 , while remote sensing applications used for investigating wide lines require only a part in 10^6 . Further, the close-in spectral purity of the reference source is multiplied to higher harmonics and impacts the noise floor when the reference has high noise levels. When using a highly pure fundamental oscillator at higher frequency, the requirements on the noise in the lock loop of a multiplier chain can be minimized. This approach is used in the Cologne spectrometer. In the JPL spectrometer a fundamental oscillator at X-band frequencies is used, while most radio observatories lock the local oscillator with millimeter wave Gunn oscillators. Since amplification and multiplication can degrade spectral purity and introduce spurs, the fundamental oscillator ultimately limits the spectral purity that the spectrometer or local oscillator can achieve.

In the laboratory the generated RF signal propagates through a gas cell before the signal reaches a sensitive detector. A variety of modulation techniques, AM, FM, and combinations thereof, can be combined with lock-in amplifiers to minimize instrumental effects. Two different implementations of submillimeter spectrometers are described in the following sections.

B. Cologne THz spectrometer

The Cologne THz spectrometer uses a series of Backward Wave Oscillators (BWO) made in Russia as fundamental oscillators operating in the range of 53 to 1200 GHz. Each BWO has an electronic tuning range of 30 to 50 % without any mechanical tuning element. The BWOs are used as a high power monochromatic source in fundamental mode required for sensitive detection of weak transient molecules or they serve to pump quasi-optical THz frequency multipliers. Figure 2 shows the Cologne spectrometer setup including its phase-lock loop circuit, the quasioptical multiplier setup, and the absorption cell with the liquid helium cooled InSb detector. The backbone of the PLL circuit is the subharmonic mixer that combines a multiple of a millimeter wave

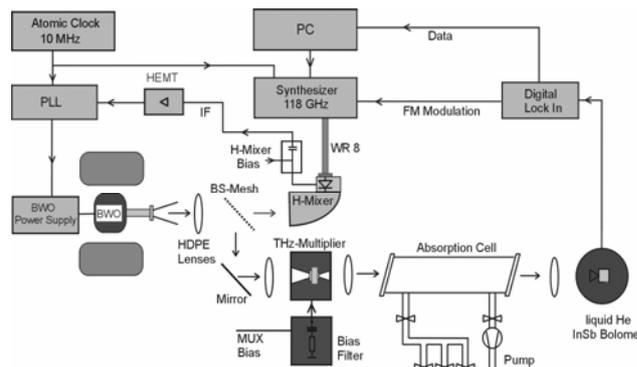


Fig. 2: Block diagram of the Cologne THz Multiplier spectrometer.

synthesizer (78 – 118 GHz) signal quasioptically with a fraction of the BWO power. The resulting intermediate frequency at 350 MHz is amplified with a low noise HEMT and then fed to the phase discriminator, which provides the control signal after being processed by the loop filter to phase- and frequency-lock the BWO [21]. The typical loop bandwidth is about 2 MHz.

BWOs typically generate several 10 mW power up to at least 810 GHz, and deliver the power into an overmoded waveguide which requires a good quasioptical matching between BWO and single mode horn antenna of the THz-tripler. The phase locked BWO system has a limited frequency control provided by the lock loop which allows for approximately 1 GHz of instantaneous tuning at the output frequency before the high voltage power supply and the lock loop parameters require re-adjustment.

The Cologne spectrometer takes advantage of the spectral purity of the BWO. This feature plus a subharmonic mixer which generates negligible harmonics and sideband frequencies at the main optical beam, assure that the spectrometer system is free of spurious signals except a weak (<-40dB) amount of 2nd harmonic from the BWO. A disadvantage of this approach is the need for two lock loops; one in the millimeter synthesizer and the other for the BWO. It also requires a high voltage supply (up to several kV) and 1.2 Tesla magnets for focusing the electron beam of the BWO. The BWO spatial mode quality is generally not an issue for fundamental mode spectroscopy, since most detectors in the submillimeter wavelength couple well to multiple modes.

The BWOs have been successfully used with planar diode multipliers in the past [13]. Several multipliers developed for HIFI have been tested using BWOs, because solid-state pump multiplier chains at frequencies from 800 to 900 GHz were still under development. The spectrometer in Cologne was utilized to characterize 1.9 THz triplers and 2.7 THz triplers. With this spectrometer, transition frequencies up to 2.3 THz were observed on molecular species, like D₂O, HDO, NH₂D and ND₂H. To our knowledge, this setup was the first THz multiplier spectrometer to open the frequency range above 2 THz to broadband high resolution spectroscopy.

C. JPL Frequency Multiplier Submillimeter Spectrometer

The spectrometer at JPL utilizes a fundamentally different approach from the one in Cologne. The spectrometer is built around a commercial core of microwave and millimeter components and relies on direct multiplication and amplification to the submillimeter and THz frequencies. In this approach, it is not possible to use the intrinsic spectral purity of a millimeter or submillimeter fundamental oscillator and PLL to clean-up the signal. As a result, the main requirement is that the input signal is spectrally pure and as free of spurs as possible. The advantage to the approach is that the spectrometer requires only one lock loop under full computer control. This allows tuning anywhere in the desired frequency band with a minimal stabilization time determined by the synthesizer and bias voltages. Only the frequency chains have to be changed to cover different frequency ranges, but the source unit remains the same. This allows the spectrometer to utilize any multiplier source built for HIFI, ALMA or other application that can be driven in the 70-120 GHz range. No quasi-optical coupling of the fundamental source is required because all components have input and output waveguides.

Several modifications are required to achieve the desired spectral purity. First, a tracking YIG filter is used at the output of the synthesizers to reduce the harmonic content and spurious content. Second, the W-band MMIC amplifiers [4] are operated in compression. Lastly, the limited ~15% bandwidth of the higher power amplifiers prevent the 5th and 7th harmonics of the millimeter wave sixtupler from being transmitted to the multiplier chain. A WR-10 waveguide filter could be used as well, but this has been so far proven unnecessary. The generated RF signal is quasi-optically guided through the sample cell and detected by a sensitive detector such as a 4 K cooled InSb or 2 K cooled Si bolometer. For the measurement of absorption lines, the entire frequency band of frequency multiplier chain can be covered by increasing or decreasing the synthesizer in small frequency steps. The smallest increment is limited by the synthesizer's resolution. Different modulation modes can be selected to acquire the spectroscopic data. A more detailed description of the spectrometer is provided in [18].

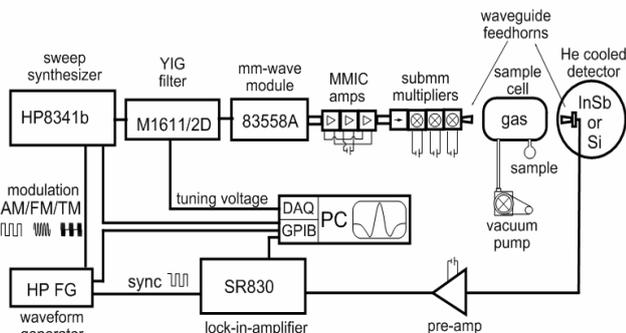


Fig. 3. Block diagram of the JPL Direct Synthesis Spectrometer.

III. CASCADED FREQUENCY CHAINS

Many of the solid-state frequency chains used in the JPL spectrometer were developed for the HIFI instrument of Herschel. Each chain contains a cascade of three or four frequency doublers or triplers starting from W-band. These modules [6] were designed for wide band operation at 120 K and high efficient power conversion without mechanical tuners. Only electrical tuning with the bias supply is required, which simplifies the operation and enables computer control. Nearly 80% of frequency coverage between 0.15 to 2 THz and partial coverage from 2.4 to 2.7 THz were achieved by cascading a x8 or x12 chain with a single diode doubler/tripler. The input power of the x12 multiplier was provided by a 100-250 mW 71-82 GHz amplifier and the x8 by a 100-200 mW 100-108 GHz amplifier. This signal was multiplied by frequency doublers or triplers up to the THz range. Several fraction of one microwatt at THz frequencies were sufficient to perform sensitive spectroscopy. Coverage of 400-720 GHz was achieved with two Virginia Diodes multipliers. The x8 JPL chain can be used to cover 720-840 [11], a x10 VDI chain covers 770-860 GHz, the JPL x12 covers 840-960 GHz, a JPL x12 covers 1060-1220 GHz [22] and a JPL x18 covers 1575-1700 GHz [23].

IV. SPECTROSCOPY

Ultimately most submillimeter frequency multipliers are used to perform spectroscopy. Laboratory spectroscopy can provide a wealth of detailed information on the source performance. The next section discusses a number of multiplier measurements that can be achieved spectroscopically.

A. Power bandwidth

The important characteristics of any submillimeter source are the output power and bandwidth, which are determined when the RF output in CW mode is maximized at nominal bias parameters. For this characterization, the bias conditions on the frequency multipliers are adjusted to be in the safe range [24] over the entire frequency scan. Safe bias conditions are defined that no excessive forward currents or any reverse currents are induced in the multiplier diodes while the frequency is incrementally changed at constant RF input level. To determine the total power content in a spectrometer setup, the RF signal is AM modulated. If the dynamic range of the detector is exceeded, the power may be attenuated. In most of the cases several sheets of paper are sufficient to prevent saturation of the detector. The total power measurement gives the shape of the output power convolved with the frequency dependent throughput and the characteristic of the optics, sensitivity of the detector, and atmospheric absorption. Once care has been taken to minimize the frequency dependent effects, the multiplier pass band can be determined. For quantitative measurements the detector's responsivity has to be known.

In Figure 4 a total power sweep of a 1600 GHz frequency chain is displayed. The measurement was performed through

a 1.6 meter long gas cell with 150 mTorr of methanol. The step size was 2.5 MHz or about 20 times higher resolution than the one available for the Fourier transform infrared spectrometer system. The red stick spectra present the predicted methanol ground state lines and relative intensity. The frequency coverage can be extracted from the data once the effects of the atmosphere's absorption are accounted for. In this case the dip in the middle is due to a strong water absorption line located at 1.604 GHz and the RF characteristic of the last stage multiplier. When the optical path is purged with dry Nitrogen, the absorption will be reduced.

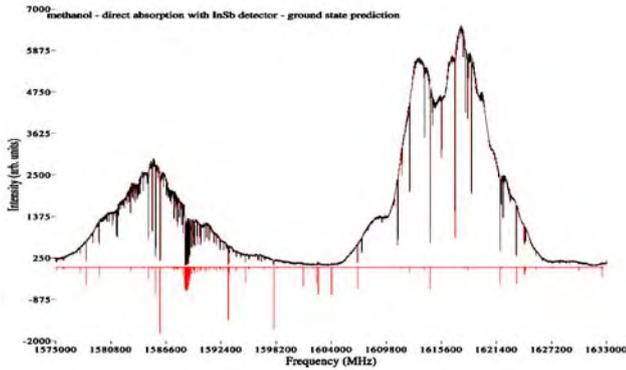


Fig. 4: Total power sweep from 1575 GHz to 1633 GHz with a 1600 GHz frequency chain used in Band 6 for the HIFI instrument in HSO

B. Extraction of noise level and harmonic content

One important consideration for multipliers is to investigate whether the total amount of power is generated in the desired harmonic. For this matter, spectroscopy on well known molecular transitions has to be performed.

The line strength of molecular transitions can be determined with high accuracy by measuring the electric dipole moment and applying the selection rules [25] for the transition. The JPL spectral line catalog [26] and the CDMS [27] provide the line strength for many molecules in $\text{Log}(I(T))$ format where the temperature (T) is 300 Kelvin. The peak absorption for pressure broadened lines is

$$\alpha_{\max} = \frac{I(T)}{\Delta\nu} \left(\frac{T_0}{T} \right) \times 102.458 \text{ cm}^{-1}. \quad (1)$$

Here $\Delta\nu$ is the half width at half height of the line at 1 Torr in MHz. The attenuation (A) in a cell of length (L) in cm is given by:

$$A = \alpha_{\max} L \times 4.3429 \text{ dB}. \quad (2)$$

Since the catalogs generally do not include the contribution for excited vibrational states the line strength should be divided by the vibrational partition function given below:

$$Q_v = \left(\sum_{v_i} e^{-v_i h \omega_i / kT} \right) \left(\sum_{v_{2i}} e^{-v_{2i} h \omega_{2i} / kT} \right). \quad (3)$$

where the v_i is the number of quanta in the i -th of the $3N-6$ vibrational modes. Vibrational states above 1000 cm^{-1} (wavenumber, 1 cm^{-1} is equal to 29.97925 GHz) in energy contribute less than a 1% correction. When this is done for the Q branch feature in figure 5, the absorption is expected to be

between 18.9 and 19.7 dB in the band head in good agreement with the observed transmission. A note of caution is that the detector must be sensitive to the other possible harmonics as well. This technique determines only if there is power at other frequencies, but it cannot distinguish between noise and harmonic content.

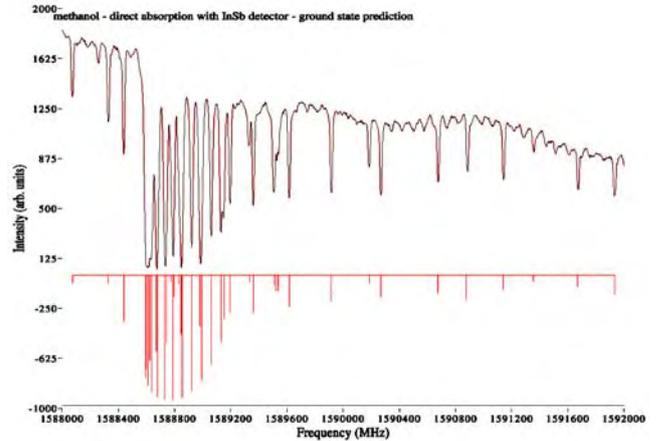


Fig. 5: Determination of noise level and harmonic content. Displayed is only a small section of figure 4 from 1588 to 1593 GHz.

C. Harmonic content

The harmonic content can be directly determined by spectroscopic measurements on known molecules with relatively strong absorption features with known frequencies and intensities in all the possible harmonics. The spectrum is measured at low pressure in the gas cell in FM or tone burst modulation. The harmonic content can be determined by the ratio of the expected line strength in the fundamental harmonic to the other harmonics. The spectrum in Figure 6 is the one for N_2O in natural isotopic abundance in the frequency range from 1.0891 THz to 1.0907 THz. The 18-O has a 0.25% natural abundance and the 15-N isotope of one of the nitrogen atoms has an abundance of 0.36%. Considering the envelope of the total power we determined a content of -27 (+/-2) dB from the fourth harmonic on a balanced 1.2 THz tripler [22]. A rich molecular spectra is required to perform a

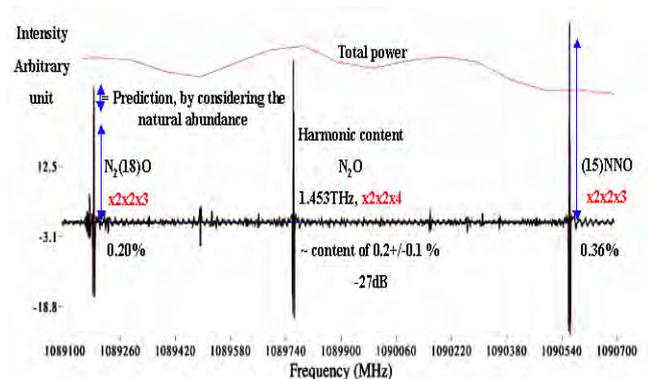


Fig. 6: Harmonic content of a 1200 GHz balanced frequency multiplier operated at 1.09 GHz with fundamental frequency range from 88 to 107 GHz. N_2O was used as molecule.

complete analysis of the pass band. This measurement is an example of how to estimate the harmonic power content. A suppression of at least 20 dB has been measured for every tested balanced multiplier designs including doublers, triplers, and quintuplers. In these designs even or odd harmonics are suppressed internally in the circuit. This suppression is essential to reduce the contribution of the next higher harmonic efficiently. In the unbalanced designs, such as single diode configurations, the next higher harmonic cannot be suppressed by the circuit symmetry. Just about all the multiplier designs with matching waveguide structure possess a common design feature which is the cut-off of the lower harmonics by the output waveguide, but all the higher contents can propagate to the output. The generation of harmonics is strongly frequency dependent, tunable by the bias point, and impacted by the level of input RF power.

The harmonic content of a single diode circuit a 2.7 THz tripler was measured to be -6dB to the next lower harmonic (second) which was much stronger than the targeted third harmonic. Initially, the low expected power available at 800-900 GHz suggested that a single diode would work more efficiently than a design with several diodes. Further, the difficulty in terminating unwanted harmonics should be appropriately considered in any such trade-off. Currently, power levels on the order of 1 mW at these frequencies suggest that balanced configurations with two diodes at frequencies above 2 THz is now the better design option than the single diode configuration.

D. Noise level

One of the important considerations in designing a receiver is the expected noise level of the local oscillator. In an ideal design it should contribute negligibly to the overall receiver temperature. These receiver utilize SIS or HEB [28] mixers which are the most sensitive detectors up-to-date to test the noise of the LO. However, there are also a number of spectroscopic techniques that can be used to determine if the noise level is significant.

Any source suitable for use as a local oscillator should be noise-limited by the detector in spectrometers. In this case the signal to noise ratio of the detected spectra will improve in proportion to the Noise Equivalent Power (NEP) of the detector used. However, the contribution of the thermal background at 300 Kelvin limits the detectors sensitivity. Without appropriate filters there is no benefit on NEPs better than 10^{-16} , which is substantially worse than narrow banded heterodyne detection. A series of measurements with progressively more sensitive detectors can be made to verify that the signal to noise ratio on weak features improves as expected. The result of this method can't prove that the source will work as a local oscillator, but it will indicate if the source has high noise content.

The other concern is the phase noise generated when frequency multipliers are cascaded. Since the observed spectra are a convolution of the line width of the signal source and the line width of the observed molecule, a quantitative

measurement of the signal source line width is possible. Molecular spectra pressure broadens according to the linear relationship:

$$\Delta\nu = 1/2\pi\tau. \quad (4)$$

where τ is the mean time between collisions. Since the Doppler contribution to the line width is directly calculable from the temperature at atomic weight, plotting the pressure broadened line width using AM modulation corrected for Doppler effects will give a slope and a zero intercept. The slope is the pressure broadening constant and the intercept is a measure of source line width [29]. Due to measurement uncertainties the accuracy is generally a few % of the molecular Doppler line width, but this method is sufficient to identify real problems with the phase noise.

E. Molecular Spectroscopy

An advantage of wide frequency range molecular data sets is the ability to apply infrared techniques where all the absorption or emission lines within the frequency range are measured. Once this is performed, computer aided methods can be used to determine the relationship between observed and calculated transitions. This is especially important when very complex spectra of traditional molecular models can not describe the existing quantum mechanic model of the molecule investigated. Measurements performed on molecules of interest allows for extension of existing databases by including more rotational and vibrational states at higher quantum numbers. Since most of the existing molecular constants cannot be used to extrapolate accurate transition frequencies (see figure 7) over the frequency ranges of Herschel, ALMA and SOFIA, it is necessary for exact astronomical interpretation of spectra to perform laboratory measurements in the THz regime of molecules of interest.

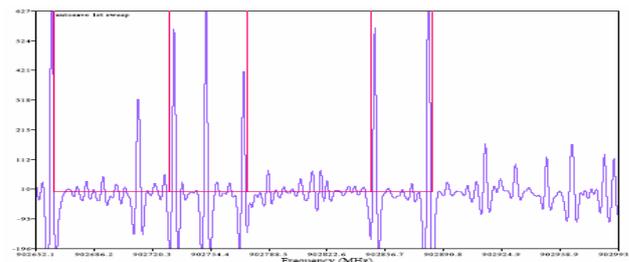


Fig. 7: Comparison of predicted and measured transitions of methanol between 902.6 to 902.9 GHz. The difference in frequency is more than the linewidth of the transitions.

V. CONCLUSION

The availability of all-solid-state frequency sources enables "IR" spectroscopy techniques to be used in the far-infrared frequency regime. With broadband frequency sweeps at THz frequencies, molecular and atomic transitions can be detected efficiently allowing computer aided processing and identification of more states and energy levels. The outcome is that precise predictions above 2 THz will be achieved, which are essential for interpretation of all radio astronomy data and the planning of future missions like SAFIR [30].

Further, spectroscopy provides a powerful diagnostic tool for characterization of the bandwidth, spectral purity, noise level, and the harmonic content of local oscillator sources. The characterization of a number of LO chains for the HIFI instrument demonstrated that balanced multiplier designs have surprisingly sufficient suppression of higher harmonics for example 2nd, 3rd, 4th etc., while those with unbalanced designs can be remarkable poor. A conclusion of this study is that extreme care should be taken to limit the harmonic content of local oscillators in HEB applications, where ghosts of strong lines could be observed with harmonic content which are more than 60 dB below the carrier. This will be a great challenge for any multiplier to overcome and should be considered in the design of a receiver system.

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REFERENCES

- [1] S. Martin, B. Nakamura, A. Fung, P. Smith, J. Bruston, A. Maestrini, F. Maiwald, P. Siegel, E. Schlecht, I. Mehdi, "Fabrication of 200 to 2700GHz Multiplier Devices using GaAs and Metal Membranes," *IEEE MTT-S Int. Microwave Symp.*, Phoenix, Arizona, May 20-25, 2001.
- [2] M.W. de Graauw, N.D. Whyborn, E. Caux, T.G. Phillips, J. Stutzki, K. Wafelbakker, "The Herschel HIFI instrument," *Proc. SPIE* vol. 5498, 2004.
- [3] ALMA web-side: <http://www.alma.nrao.edu/>.
- [4] R.R. Ferber, J.C. Pearson, T.C. Gaier, L.A. Samoska, F.W. Maiwald, M. Wells, A. Campbell, and G. Swift, P. Yocom, K.T. Liao, "W-Band MMIC Power Amplifiers for the Herschel HIFI Instrument," *Proc. 14th Int. Symp. on Space THz Tech.*, Tucson, 22 April 2003.
- [5] N.R. Erickson, G. Narayanan, R.P. Smith, S.C. Martin, I. Mehdi, T.W. Crowe, W.L. Bishop, "Planar Frequency Doublers and Triplers for FIRST," *Proc. 11th Int. Symp. on Space THz Tech.*, pp 543-551, 2000.
- [6] J.S. Ward, E. Schlecht, G. Chattopadhyay, A. Maestrini, J. Gill, F. Maiwald, H. Javadi, I. Mehdi, "Capability of THz Sources Based on Schottky Diode Frequency Multiplier Chain," *IEEE MTT-S Int. Microwave Symp. Digest*, Fort Worth, TX, pp. 1587-1590, June 2004.
- [7] F. Maiwald, E. Schlecht, A. Maestrini, G. Chattopadhyaya, J. Pearson, D. Pukala, I. Mehdi, "THz frequency multiplier chains based on planar Schottky diodes," *Proc. of SPIE*, vol. 4855, pp. 447-458, Waikoloa, Hawaii, 22-28 August 2002.
- [8] J. Ward, F. Maiwald, A. Maestrini, G. Chattopadhyay, E. Schlecht, J. Gill, I. Mehdi, "1400-1900 GHz Local Oscillators for the Herschel Space Observatory," *Proc. 14th Int. Symp. on Space THz Tech.*, Tucson, AZ, 22-24 April 2003.
- [9] D. Porterfield, T. Crowe, R. Bradley and N. Erickson, "A High-Power, Fixed-Tuned, Millimeter-Wave Balanced Frequency Doubler," *IEEE Trans. Microwave Theory Tech.*, vol. 47, p419, 1999.
- [10] E. Schlecht, G. Chattopadhyay, A. Maestrini, D. Pukala, J. Gill, S. Martin, F. Maiwald, I. Mehdi, "A High-Power Wideband Cryogenic 200 GHz Schottky "Substrateless" Multiplier: Modeling, Design and Results," *Proc. of the 9th Int. Conf. on THz Tech.*, Charlottesville, VA, October 14-16, 2001.
- [11] G. Chattopadhyay, E. Schlecht, J. Gill, S. Martin, A. Maestrini, D. Pukala, F. Maiwald, I. Mehdi, "A Broadband 800 GHz Schottky Balanced Doubler," *IEEE Microwave and Wireless Components Letters*, Vol. 12, No. 4, pp. 117-118, April 2002.
- [12] P. Zimmermann, "Multipliers for THz Local Oscillators," *Proc. SPIE* vol. 3357, pp. 152-158, 1998.
- [13] F. Maiwald, F. Lewen, B. Vowinkel, W. Jabs, D.G. Paveljev, M. Winnewisser, G. Winnewisser, "Planar Schottky Diode Frequency Multiplier for Molecular Spectroscopy up to 1.3 THz," *IEEE Microwave and Guided Wave Letters*, Vol. 9, No. 5, May 1999.
- [14] F. Maiwald, S. Martin, J. Bruston, A. Maestrini, T. Crawford, I. Mehdi, J.R. Burke, R.R. Lay, M.S. Loo, N.J. Livesey, T.A. Lungu, G.L. Manney, L.L. Nakamura, V.S. Perun, B.P. Ridenoure, Z. Shippony, P.H. Siegel, R.P. Thurstans, R.S. Harwood, H.C. Pumphrey, M.J. Filipiak, "The UARS and EOS Microwave Limb Sounder Experiments," *J. Atmos. Sci.* 56, 194-218, 1999.
- [15] J.W. Waters, W.G. Read, L. Froidevaux, R.F. Jarnot, R.E. Cofield, D.A. Flower, G.K. Lau, H.M. Pickett, M.L. Santee, D.L. Wu, M.A. Boyles, J.R. Burke, R.R. Lay, M.S. Loo, N.J. Livesey, T.A. Lungu, G.L. Manney, L.L. Nakamura, V.S. Perun, B.P. Ridenoure, Z. Shippony, P.H. Siegel, R.P. Thurstans, R.S. Harwood, H.C. Pumphrey, M.J. Filipiak, "The UARS and EOS Microwave Limb Sounder Experiments," *J. Atmos. Sci.* 56, 194-218, 1999.
- [16] R. Guesten, et al., "GREAT: the first-generation German heterodyne receiver for SOFIA," *SPIE In. Symp. on Astronomical Telescopes and Instrumentation*, Conf. 4014, Munich, Germany, 27-31 March, 2000.
- [17] M.L. Edgar, J. Zmuidzinas, "CASIMIR: submillimeter heterodyne spectrometer for SOFIA," *SPIE Int. Symp. on Astronomical Telescopes and Instrumentation*, Vol. 4014, Munich, Germany, 27-31 March, 2000.
- [18] B. Drouin, F. Maiwald, J. Pearson, "Application of cascaded frequency multiplication to molecular spectroscopy", to be published 2005.
- [19] J.C. Pearson, R. Guesten, T. Klein, N.D. Whyborn, "The Local Oscillator System for the Heterodyne Instrument for FIRST (HIFI)," *UV, Optical and IR Space Telescopes and Instruments, Proc. of SPIE*, Vol. 4013, 2000.
- [20] G. Chattopadhyay, F. Maiwald, E. Schlecht, R.J. Dengler, J.C. Pearson, I. Mehdi, "Spurious Signal Response of Broadband Solid-State Frequency Multipliers at Millimeter and Submillimeter Wavelengths," *Int. Journal of Infrared and Millimeter Waves*, Vol. 24, No. 9, pp. 1485-1498, September 2003.
- [21] F. Lewen, R. Gendriesch, I. Pak, D. Paveliev, M. Hepp, R. Schieder, G. Winnewisser, "Phase locked backward wave oscillator pulsed beam spectrometer in the submillimeter wave range," *Rev. Sci. Instrum.* 69 (1), January 1998.
- [22] J. Bruston, A. Maestrini, D. Pukala, S. Martin, B. Nakamura, I. Mehdi, "A 1.2 THz planar tripler using GaAs membrane based chips," *Proc. 12th Int. Symp. Space THz Tech.*, pp. 310-319, 2001.
- [23] A. Maestrini, J. Ward, H. Javadi, C. Tripon-Canseliet, J. Gill, G. Chattopadhyay, E. Schlecht, I. Mehdi, "Local Oscillator Chain for 1.55 to 1.75 THz with 100 mW Peak Power," Submitted to IEEE MWCL.
- [24] F. Maiwald, E. Schlecht, R. Lin, J. Ward, J. Pearson, P. Siegel, I. Mehdi, "Reliability of cascaded THz frequency chains with planar GaAs circuits," *Proc. 15th Int. Symp. on Space THz Tech.*, Amherst, MA, 27-29, April 2004.
- [25] W. Gordy, R.L. Cook, 1984, *Microwave Molecular Spectra*, John Wiley & Sons, New York.
- [26] H.M. Pickett, R.L. Poynter, E.A. Cohen, M.L. Delitsky, J.C. Pearson, H.S.P. Müller, "Submillimeter, Millimeter, and Microwave Spectral Line Catalog," *J. Quant. Spectrosc. & Rad. Transfer* 60, 883-890 (1998). <http://spec.jpl.nasa.gov/>.
- [27] H.S.P. Müller, F. Schlöder, J. Stutzki, G. Winnewisser, "The Cologne Database for Molecular Spectroscopy, CDMS: A Useful Tool for Astronomers and Spectroscopists," *J. Mol. Struct.* 742, 215-227 (2005). http://www.ph1.uni-koeln.de/vorhersagen/catalog/main_catalog.html.
- [28] J. Zmuidzinas, P. Richards, "Superconducting Detectors and Mixers for Millimeter and Submillimeter Astrophysics," *Proc. of IEEE*, Vol. 92, No. 10, Oct. 2004.
- [29] B.J. Drouin, J. Fischer, R.R. Gamache, "Temperature dependent pressure induced lineshape of O3 rotational transitions in air," *Journal of Quantitative Spectroscopy & Radiative Transfer* 83 (2004) 63-81.
- [30] D.J. Benford, J.W. Kooi, "Heterodyne Receiver Requirements for the Single Aperture Far-Infrared (SAFIR) Observatory," *Proc. 14th Int. Symp. on Space THz Tech.*, Tucson, AZ, 22 April 2003.